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Photometric and Psychophysical Measurements of Exit Signs Through Smoke

by M.S. Rea, F.R.S. Clark and M.J. Ouellette

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PHOTOMETRIC AND PSYCHOPHYSICAL MEASUREMENTS OF EXIT SIGNS THROUGH SMOKE

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I. INTRODUCTION

Exit signs are important components of modern fire protection systems in buildings. They are supposed to be visible through smoke and, thus, to guide occupant evacuation. Nevertheless, the design of exit signs is not generally based upon experimental research nor upon principles of good visibility.

Several kinds of investigations have been performed on the subject of exit sign visibility through smoke. One kind of study[1-4] has followed the methodology recommended by the General Services Administration (GSA) of the United States government.[5] In these studies, determinations are made of the maximum distances from which particular signs can be seen in a smoke-filled corridor. However, an important visual parameter, the apparent size of the sign, varies with viewing distance, and, therefore its influence cannot be unambiguously evaluated. Consequently, it is more difficult to use the results of these studies as bases for recommendations of exit sign visibility.

Collins and Lerner,[6] in a second kind of study, used a combination of absorbing filters and 'veiling' luminous sources to simulate the optical properties of smoke. Whereas this approach is convenient for assessing sign visibility under controlled conditions of luminance and contrast, it does not characterize the visual conditions found in smoke, because it does not properly simulate the scattering of light, particularly scatter originating from the sign itself.

Jin[7] has developed an empirical model for predicting sign visibility through smoke. He expressed visibility as the minimum viewing distance at which the sign becomes completely obscured. Considered in the model are the luminance and the threshold contrast of the sign, ambient illumination, smoke density, and the scattering and absorbing properties of the smoke. However, this model is based upon data obtained with the GSA methodology,[5] and therefore presents the same difficulties. Further, the empirical relations established by Jin between visibility, luminance and contrast threshold are not in complete agreement with known principles of human vision.[8-10] Finally, the signs used in Jin's study were not thoroughly described so it is difficult to translate the results into design guidelines. It should be pointed out, however, that the model could be useful for making comparisons of visibility in various smokes.

Visibility-related recommendations for exit signs have been made by various sanctioning bodies throughout the world. Sign brightness, one of the most important factors determining visibility in smoke, is not specified by some of these bodies. Others do provide some guidance, but the foundations of the specifications are not adequately documented. In the United Kingdom,[11] luminance levels between 2 and 80 cd m^{-2} are recommended for trans-illuminated signs (with internal lamps behind translucent letters or backgrounds). A note in this specification suggests, however, that the "most suitable level" is between 17 to 34 cd m^{-2}. In the corresponding United States standard[12], a distinction is made between signs with (a) trans-illuminated letters and opaque backgrounds, (b) trans-illuminated backgrounds and opaque letters, and (c) trans-illuminated letters and backgrounds. For type (a), the letters must have an average luminance not less than 2 fL (6.85 cd m^{-2}) and not more than 3 fL (10.28 cd m^{-2}); for type

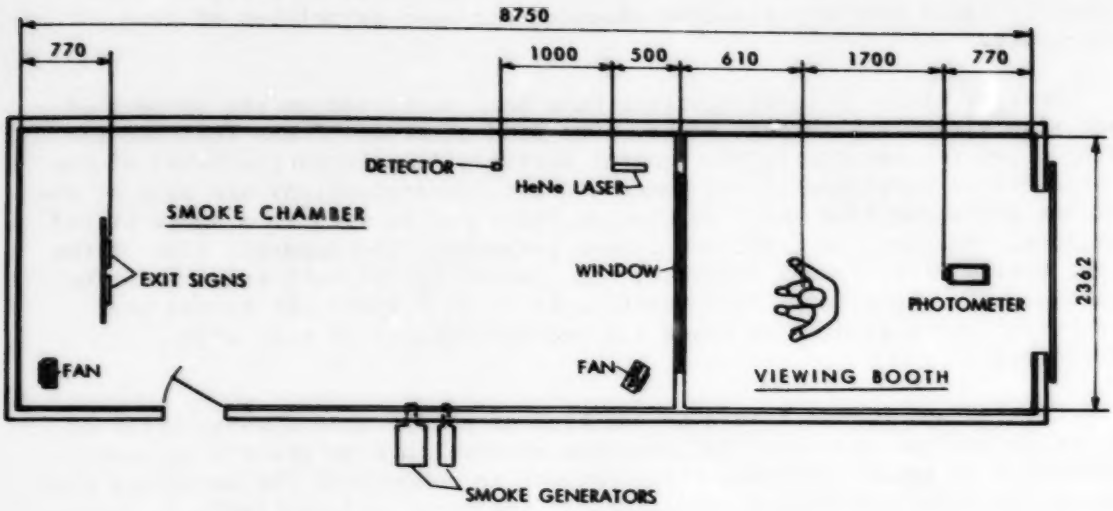

Figure 1. Floor plan of the smoke chamber and viewing booth. All dimensions in mm.

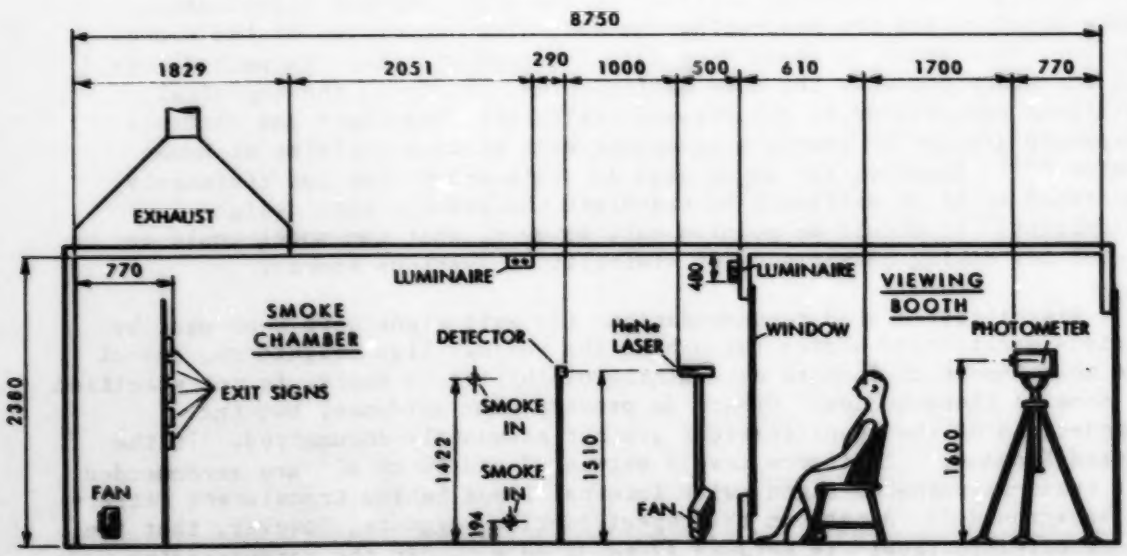

Figure 2. Side view of the smoke chamber and viewing booth. All dimensions in mm.

(b), the background must have a minimum average luminance of 3 fL, but no maximum luminance is set; for type (c), the average luminance of the brighter portion (letters or background) must be at least 6 fL.

Standards from both the United Kingdom and the United States make exceptions for "approved self-illuminated" signs. These signs are made luminous in the dark by beta radiation-induced chemiluminescence of the coating from a chamber filled with tritium ($_1H^3$) gas. In the United States,[12] these signs are permitted to have a minimum luminance of 0.06 fL (0.21 cd m^{-2}). In the United Kingdom[13] the minimum permitted initial luminance is 0.51 cd m^{-2}, and the manufacturer must specify how long the sign luminance is expected to be above 0.14 cd m^{-2}.

No specification of sign luminance appears in the National Building Code of Canada (NBC),[14] but the Canadian General Standards Board (CGSB)[15] requires that "the intensity of the light emitted by the sign shall not be less than that from a 25 W incandescent filament lamp when activated by a regular circuit". The NBC and the CGSB also differ in particulars related to visibility of exit signs, including letter size, colour, and the use of glyphs.

The differences between exit sign specifications in Canada (and elsewhere) and the lack of definitive information that might allow such specifications to be written led the CGSB and the Associate Committee of the NBC to ask the Division of Building Research, National Research Council of Canada (DBR/NRCC) to examine the visual effectiveness of some exit signs in smoke.

The purpose of the study reported here was to provide information on the visibility of selected exit signs through smoke to these Canadian sanctioning bodies. Based upon the results, which were largely consistent with well-established principles of vision and optics, some design recommendations for exit signs and emergency lighting have been proposed. A few design considerations and topics for further research have also been formulated from the data. It is hoped that the information reported here will lead to improved fire safety in Canada and elsewhere.

II. EXPERIMENTATION

Two classes of measurements were made of thirteen exit signs selected for testing: 1) broad-band photometric measurements[16] were made of the signs under clear conditions and through smoke of different types and densities; 2) sixteen observers made threshold psychophysical observations of each sign through cosmetic oil smoke.

A. Apparatus

1. The smoke chamber and viewing booth

The smoke chamber and viewing booth (Figures 1 and 2) were constructed of lumber framing covered with black polyethylene film. A 1.2 m × 2.4 m clear plastic window (transmittance, t = 0.92) of high optical fidelity separated the smoke chamber from the viewing booth. The smoke chamber contained (a) the exit signs, mounted on a stationary vertical rack, (b)

exhaust pipes from the two types of smoke-generating apparatus (just outside the smoke chamber), (c) a smoke density measuring apparatus, and (d) two fluorescent luminaires mounted near the smoke chamber ceiling. The viewing booth housed (a) on-off controls for each exit sign and the fluorescent luminaires, (b) a smoke density monitor, (c) on-off controls for smoke generation, (d) the experimenter(s), and, either, (e) the photometer and time averaging equipment or (f) a human observer.

2. The exit signs

Samples of nine exit sign designs, including some recommended for use in Canada, were chosen for the study. Appendix A describes these signs in detail. All signs were affixed to a stationary rack in the centre of the smoke chamber, 4.9 m from the window dividing the smoke chamber and the viewing booth. Colour photographs of the exit sign array in the dark and in room lighting are shown in Appendix B.

Thirteen exit signs were actually tested in this experiment. Seven electric, trans-illuminated signs and two chemiluminescent, self-illuminated signs were employed, but four of the seven trans-illuminated signs housed both incandescent and fluorescent lamps. Because the kind of lamp within a trans-illuminated sign affects the luminous quality and brightness of that sign, the seven different trans-illuminated sign designs were treated as eleven completely different signs for experimental testing.

Each trans-illuminated sign (and, where relevant, lamp type within a sign) could be turned 'on' and 'off' with switches in the viewing booth operated by the experimenter. Each self-illuminated sign could be covered and uncovered with a mechanical flap attached to a fine string manipulated from the viewing booth.

3. Smoke generation

Except for preliminary photometric testing (Appendix C), smoke was generated using a Model 3020 oil smoke generator (Les Enterprises MDG Inc., Quebec City, Quebec, Canada). This device sprayed cosmetic oil onto a hot plate; smoke was produced as the oil evaporated. The smoke was blown into the smoke chamber at floor level by compressed carbon dioxide gas. Smoke could be removed with an exhaust fan installed in the ceiling. Two 18 cm diameter fans located on the floor dispersed the smoke evenly throughout the chamber. The density and uniformity of the smoke was accurately controlled.

4. Smoke measurement

A helium-neon laser (1.0 mW) and a silicon diode photodetector were located in the smoke chamber (Figures 1 and 2) and operated continuously during testing. This monitoring device has been described in detail elsewhere.[17] Briefly, however, obscuration of the 632.8 nm wavelength laser beam was measured across a 3 m or a 1 m path. All estimates of smoke density are based upon recordings from this device and are reported in terms of optical density per meter (OD m^{-1}),

where $OD = \log_{10}(I_c/I_s)$
I_c is the recorded value without smoke (a constant value)
and I_s is the recorded value in smoke (variable values)

5. Smoke chamber lighting fixtures

Ambient illumination in the smoke chamber was provided by two lighting fixtures mounted near the ceiling (Figure 2). Each commercially available luminaire (0.3 m × 1.3 m) had a pair of F40-CW fluorescent lamps within a clear, acrylic, wrap-around prismatic lens. As with the exit signs, the ambient illumination could be turned 'on' and 'off' from within the viewing booth.

B. Photometric measurements

1. Illuminance measurements

With both ceiling luminaires 'on', horizontal plane illuminances along the centre line of the smoke chamber were obtained under smoke-free conditions, at a height of 1.7 m (Table I). At the plane of the exit sign rack, a vertical illuminance of 75 lx was obtained 1.5 m above the smoke chamber floor.

In a darkened laboratory, illuminance measurements were obtained from each exit sign at a distance of 30.5 cm normal to the centre of the face of the sign and, where applicable, 30.5 cm below the sign, normal to the centre of the downlight aperture. These values are included in Appendix A as 'general illuminances', front and below, respectively.

2. Luminance measurements of the exit signs

Photometry was performed with a Spectra Pritchard, Model 1980A, photometer fitted with a 3 mm diameter aperture on the objective lens. Some measurements under low luminances (through smoke in the dark) were achieved by time averaging 1000 readings over a 12 s interval with a 12 bit analog-to-digital converter and a microcomputer.

Table I
Smoke Chamber Illuminance at Height of 1.7 m with Room Lights 'on'

Distance from exit signs, m	Horizontal Illuminance, lx
4.6	410
4.2	500
3.9	560
3.6	730
3.3	980
3.0	1200
2.7	970
2.4	630
2.1	320
1.8	170

The photometer was positioned on a tripod 7.2 m from the exit sign rack. Except where noted, the 'general luminance' of each sign was measured through the window separating the darkened viewing booth and (a) the darkened or (b) the illuminated smoke chamber by pivoting the photometer on the stationary tripod (Appendix A). The window was cleaned routinely. The 'general luminance' was measured using a circular field aperture just large enough to cover the face of the exit sign; the measured locations and areas are indicated by dashed circles in Appendix A.

In a separate series of measurements, the luminances of several small points on the face of each exit sign were measured in a dark room using a 6 minute diameter field aperture. In Appendix A, these locations are identified by solid circles. The photometric data are also given.

3. Chromaticity measurements of the exit signs

The Model 1980A Pritchard photometer also contains, nominally, 'blue', 'red' and 'green (or V_λ)' broad band color filters. These filters were used to estimate the chromaticity coordinates[16] of the text and, where appropriate, the background, of every sign under smoke-free conditions. Several small areas of the text and of the background were measured. Chromaticity coordinates within the two sets of measurements (text and background) differed very little for any given sign. Appendix A provides typical values for each sign.

The chromaticity coordinates of a white region of Sign 1 were also measured under different densities of the cosmetic oil smoke. As shown in Figure 3, the chromaticity coordinates shifted toward larger values of x and

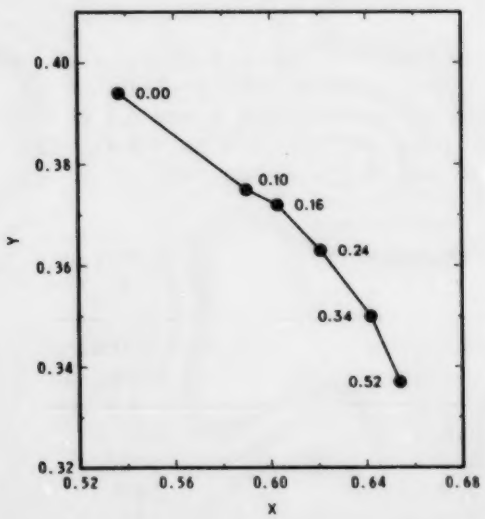

Figure 3. C.I.E. chromaticity coordinates for a white luminous region of Sign 1 at different smoke densities. The points are labeled in units of OD m^{-1}.

smaller values of y (the redder region of the chromaticity space) with increasing smoke density. Though not particularly large, this shift did demonstrate the preferential scattering of shorter wavelengths in the cosmetic oil smoke. It should be noted that such preferential scattering is not necessarily a characteristic of all smoke.[7]

C. Psychophysical observations

1. Observers

Sixteen volunteers (Table II) from DBR/NRCC made threshold visibility evaluations of each exit sign. Prior to the experiment, the eyesight of each observer was assessed with a battery of visual tests from a Keystone Ophthalmic Telebinocular and, if found colour deficient by one of the tests, with a Schmidt and Haensch anomalasope. Subjects requiring corrective lenses wore them during both the assessment and the experiment, so that all subjects had normal or better acuity in one or both eyes. Six subjects were classed as colour deficient; some details about the different classes of colour vision are given in Table II.

2. Experimental Design

Data collection was organized for subsequent analysis of variance (ANOVA) into a three-factor, repeated measures experimental design[18]. Critical smoke density (Section II.C.3) was used as the dependent variable.

Factor 1: Exit sign (13 different signs)
Factor 2: Threshold visibility criterion
adopted by the observers : 'detectability'
(can just see the sign) or 'readability'
(can just read the sign)
Factor 3: Ambient smoke chamber illumination
(lighting fixtures 'on' or 'off')

Each observer was exposed to all of the 52 (13 signs x 2 criteria x 2 levels of ambient illumination) conditions once.

3. Procedures

One observer and one experimenter sat in the viewing booth during an experimental session. Each observer faced the window and was approximately 5.2 m from the displayed sign in the smoke chamber. When the ambient illumination was 'off', observers had adapted to the darkness for at least 10 minutes before any observations were recorded.

During an experimental trial, subjects were instructed to adopt one of the two threshold criteria (detectability or readability). One exit sign was displayed in the smoke chamber, and after a uniform smoke distribution was established, the subject reported whether the exit sign was above or below the adopted threshold criterion. If it was still above threshold, more smoke was added and the experimenter asked for another judgement. When the exit sign was just below threshold, the density of the smoke across a 1 m path (Section II.A.4) was taken as the critical smoke density. These trials continued until the critical smoke densities had been obtained for all conditions or until the subject wanted to stop.

Table II
Characteristics of Observers

Subject no.	Sex	Age	Colour Vision[1]
1	M	63	T
2	M	33	T
3	M	64	T
4	M	22	T
5	M	43	T
6	M	21	T
7	M	19	T
8	F	22	T
9	M	24	T
10	M	46	T
11	M	20	Td
12	M	47	Tp
13	M	56	Dp
14	M	37	Dp
15	M	32	Tp
16	M	24	Td

[1]Trichromats (T), or colour normals, are people having all three types of cone photopigments; short (blue), middle (green), and long (red) wavelength sensitive cone types present in the retina. The spectral sensitivity of the long wavelength cone is shifted toward the centre of the visible spectrum relative to colour normals for protanomolus trichromats (Tp). The spectral sensitivity of the middle wavelength cone is shifted toward the long end of the visible spectrum relative to colour normals for deuteranomalous trichromats (Td).

Dichromats (D), or colour blinds, are people with only two of the three types of cone photopigments. Protanopes (Dp) are dichromats effectively missing the long wavelength sensitive cone.

In this document, all observers with reduced sensitivity to the long wavelengths in the visible region of the spectrum (Tp and Dp observers) are labeled as 'protans'. Besides abnormal colour perception, protans have reduced overall luminous efficiency. Thus luminous stimuli emitting energy in the long wavelength region of the visible spectrum will be less efficacious in evoking brightness perceptions in protans than in colour normals.

Deuteranomalous trichromats are also called deutans in this report.

For a more detailed explanation of the various types of colour vision and its influence on colour and brightness perception, see references 16 and 19.

Several trials were conducted during an experimental session. These sessions varied in duration, depending upon the motivation of the observer; he or she could stop at any time. Between 4 and 8 hours over one or two days were required to obtain all the data for a single subject. Signs were typically presented in increasing order of brightness to shorten session length. Sometimes it was necessary, however, for the experimenter to exhaust some smoke from the chamber so that subjects could make threshold judgements of dimmer exit signs.

III. RESULTS AND DISCUSSION

A. The results of the analysis of variance (ANOVA)

Table III presents the results of the three-factor, repeated measures ANOVA using critical smoke density as the dependent variable. All of the main effects (sign (S), threshold criterion (C), and ambient illumination (R)) and all of the two-way interactions (S×C, S×R, and C×R) were significant at a confidence level of $p < 0.003$; the three-way interaction (S×C×R) was not significant.

B. The brightness of the exit signs

The ANOVA shows that the thirteen exit signs were significantly different in their visibility through smoke (Table III). Figure 4 graphically characterizes this significant main effect; it shows the relation between 'general luminance' measured without room lights (Section II.B.2) for the thirteen signs and critical smoke density (II.C.3), averaged over the two other experimental factors, threshold criterion and ambient illumination.

Table III
Analysis of Variance

Source of Variation	Sum of Squares	df	Mean Square	F	p
S	20.700	12	1.730	286.00	0.000
R	16.000	1	16.000	2653.00	0.000
C	1.340	1	1.340	223.00	0.000
S × R	1.540	12	0.128	21.30	0.000
S × C	0.182	12	0.015	2.52	0.003
R × C	0.085	1	0.085	14.10	0.000
S × R × C	0.076	12	0.006	1.05	0.404

S: exit sign
R: room lights ('on' or 'off')
C: threshold criterion ('detectability' or 'readability')

Dependent variable: critical smoke density

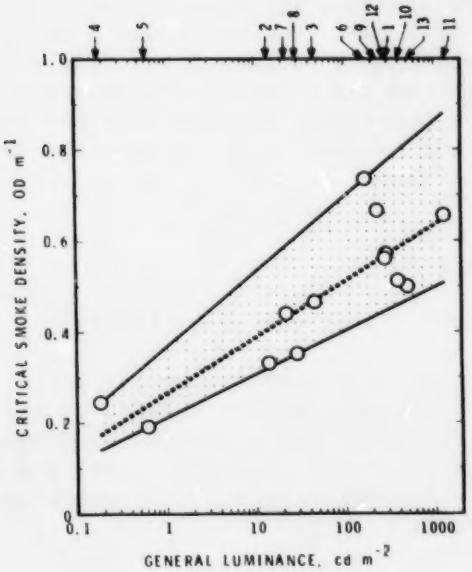

Figure 4. Critical smoke densities for the 13 exit signs as a function of general luminance (sign numbers at top).

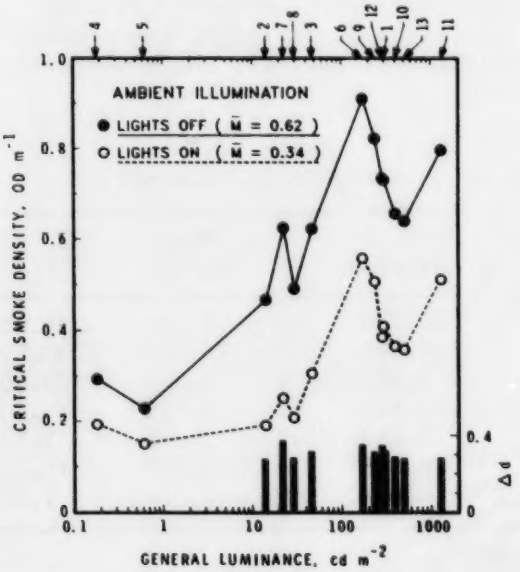

Figure 5. Critical smoke densities for the 13 exit signs as a function of general luminance at both levels of ambient illumination (sign numbers at top). Mean values of critical smoke density for the two levels of ambient illumination are inset. Columns at bottom show, for each sign, the difference in critical smoke density (Δd) between the two levels of ambient illumination.

General luminance is only one of many ways to characterize these signs; the ANOVA is performed without regard for the luminances of the signs. However, general luminance is a reasonable and convenient way to characterize these signs because there is a strong, positive linear relationship ($r = 0.86$) between the logarithm of general luminance and critical smoke density (dashed line in Figure 4). This strong positive correlation leads one to conclude, then, that brighter exit signs will be more visible in smoke.

Nevertheless, other factors associated with the signs, the environment and the observers contributed to the variation (shaded area in Figure 4) about an idealized linear model relating log general luminance and critical smoke density. Some of the factors are described below.

C. The ambient illumination

Light from ambient illumination in the smoke chamber significantly reduced the visibility of all exit signs (Table III). Figure 5 documents the statistically different average ($\bar{M}$) critical smoke densities for the two levels of ambient illumination, 'on' and 'off'.

Figure 5 also illustrates the significant interaction between the factors exit sign (S) and ambient illumination (R) (S×R term in Table III). Ambient illumination affected the visibility of some exit signs more than that of others. This is illustrated by the heights of the columns at the bottom of Figure 5; the higher the column, the more the signs were affected by ambient illumination. The columns for Signs 4 and 5 were not included in this figure because the general luminances of these two signs (Appendix A) changed substantially under ambient illumination. It should be noted that deleting the data for these two signs did not affect the significance of the S×R interaction nor any other term in the ANOVA. Adequate interpretation of this interaction requires a more sophisticated parametric study than was performed here.

Ambient illumination was also important to the critical smoke density required to reach the two visibility threshold criteria, 'detectability' and 'readability'. The significant interaction (C×R in Table III) between the factors ambient illumination (R) and visibility threshold criterion (C) is shown in Figure 6. The better optical quality created when the room lights are 'off' (i.e. when there is less scattered light) not only enables subjects to see the signs better, but it also enhances the differences between the critical smoke densities required for detectability and readability (0.10 OD m^{-1} versus 0.06 OD m^{-1}).

D. The threshold criteria

Significantly higher smoke densities were required to reach the 'detectability' criterion than the 'readability' criterion (Table III). Figure 7 documents the statistically different average ($\bar{M}$) critical smoke densities for the two threshold criteria.

There was a significant interaction (S×C) between the factors exit sign (S) and threshold criterion (C), also depicted in Figure 7. The columns at the bottom of the figure represent the differences in mean critical smoke densities for each sign at these two criteria; if there had not been a

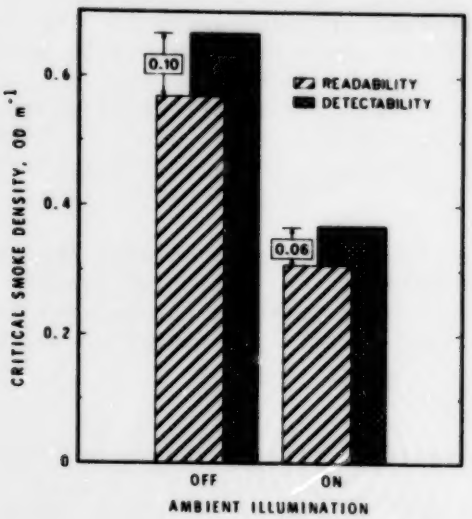

Figure 6. Critical smoke densities for the 13 exit signs for both threshold criteria at the two levels of ambient illumination.

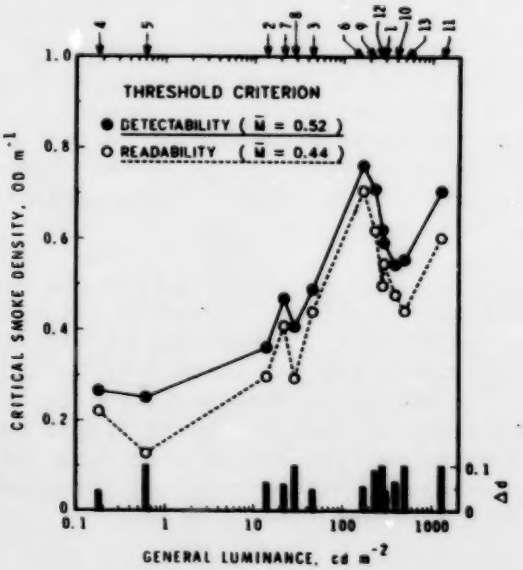

Figure 7. Critical smoke densities for the 13 exit signs as a function of general luminance at both threshold critera (sign numbers at top). Mean values of critical smoke density for the two threshold criteria are inset. Columns at bottom show, for each sign, the difference in critical smoke density (Δd) between the two threshold criteria.

significant interaction between the factors exit sign and threshold criterion, the heights of these columns would be statistically indistinguishable.

1. Scattered light created by the signs

As described in the previous section, scattered light from ambient illumination reduced the visibility of the exit signs. Although not studied parametrically in this experiment, there was an indication that scattered light from luminous, but unlettered, areas of a sign reduce its readability relative to its detectability.

Any aperture in an exit sign (e.g. a downlight) will increase the amount of light scattered in smoke through which a sign must be detected or a letter must be read (Section III.C). However, scattered light in smoke will likely reduce the readability of a letter more than the detectability of the sign. Detection of a sign through smoke is determined largely by the total amount of light emitted from the sign in any direction, whereas readability of a letter through smoke depends more upon the optical fidelity of the atmosphere. In other words, one may still be able to discern the location of a luminous sign in smoke even if spatial details, like the lettering, are obscured. Thus, luminous features of signs unimportant for reading will adversely affect readability more than detectability.

Text size and the luminous contrast between text and background are important for exit sign readability but unimportant for exit sign detectability. Scattered light will reduce the readability of low contrast letters (e.g. Signs 8 and 13) more than high contrast letters (e.g. Signs 2 and 10).* Thus the columns at the bottom of Figure 7 are generally higher for the low contrast lettered signs than the high contrast ones. Smaller text is also more susceptible to readability losses from scattered light. This is evident from the higher columns in Figure 7 for those Signs (5, 8, and 13) which have smaller lettering.

2. Very dim exit signs

The general luminances of the trans-illuminated signs were approximately the same with and without ambient illumination, but, as noted in Section III.C, the luminances of the self-luminous signs (Signs 4 and 5) were quite different under these two conditions (Appendix A). The results in Figure 8 support the hypothesis that a different class of photoreceptor was used by subjects to detect these very dim signs when the smoke chamber lights were 'off'.

There are two classes of photoreceptors, rods and cones, in the human eye that operate at different brightness levels.[16] The more sensitive rods are used under dim conditions (below approximately 0.001 cd m^{-2}) and cones are used under bright conditions (above approximately 3 cd m^{-2}). In the mesopic region (between 0.001 and 3 cd m^{-2}) both rods and cones operate. These photoreceptors differ not only in terms of the brightness levels at which they operate, but also in terms of the amount of spatial detail that

*For these purposes, contrast may be considered as the ratio of text to background luminances on the sign face. Appendix A provides text and background spot luminances on each sign.

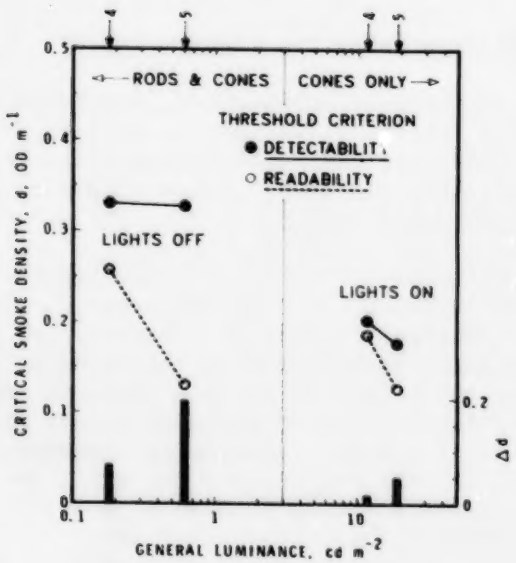

Figure 8. Critical smoke densities for the two self-luminous signs at the two threshold criteria as a function of general luminance (sign numbers at top). Columns at bottom show, for each sign, the difference in critical smoke density (Δd) between the two threshold criteria.

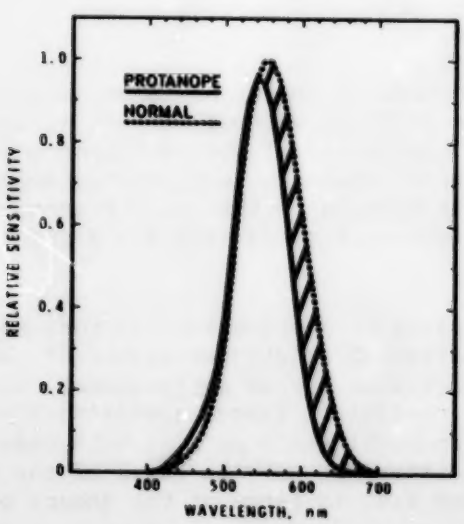

Figure 9. The relative spectral sensitivity of colour normals and protanopes normalized at 540 nm (after references 16 and 19).

they can resolve. Only cones can be used to see fine detail or to read letters of the size encountered in this experiment.

With the ambient illumination 'on', the brightnesses of the chemiluminescent signs were above 3 cd m^{-2}, so cones were used both to detect and to read these two signs (and all of the trans-illuminated signs). With room lights 'off', however, their brightnesses were below this level. Under these dim, mesopic conditions, cones were needed to read the signs but rods could be used to detect them. The sensitivity range of the eye was thus extended at the lower luminances (left side of Figure 8) relative to that at higher luminances (right side of Figure 8).

E. The spectral sensitivity of the subjects

Observers with different cone spectral sensitivities were intentionally included in this study; colour normals, protans and deutans were tested (see Table II). It is reasonable to suppose that the spectral sensitivity (or colour vision) of subjects would be important to the outcome of this experiment. Protans, for example, should be less sensitive (give lower critical smoke densities) to red signs (e.g. Signs 6, 7, 9, and 12), because these subjects have attenuated cone (photopic) luminous efficiencies at long wavelengths (Figure 9). In fact, protans should be less sensitive to any sign at photopic (high) brightnesses.

Unlike the other variables discussed before, however, colour vision cannot be randomly assigned to subjects, and other personal factors that could affect visibility can be easily confounded with the subject's spectral sensitivity. For example, the small group of subjects categorized as protans in this experiment could, by chance, also have been more cautious or conservative in their psychophysical judgements. These psychological factors would also contribute to lower critical smoke densities, and it is impossible, just with this test, to know whether the differences between protans and the other subjects were due to colour vision alone. Fortunately, there is a good understanding of colour vision and its consequences to visibility.

Despite potential confounding, colour vision was included in another ANOVA with the original three experimental factors (exit sign, threshold criterion and ambient illumination). The sixteen observers were categorized according to colour vision as (a) colour normals ($n = 10$), (b) deutans ($n = 2$), or (c) protans ($n = 4$). The new ANOVA showed that colour vision was a significant factor, and a subsequent statistical test (the Tukey test of paired comparisons[18]) showed that the protan group was significantly worse than the colour normal and deutan groups with respect to the average critical smoke density required to reach threshold ($p < 0.001$). There was also a significant interaction between the factors colour vision and exit sign ($p < 0.03$). Both results are illustrated in Figure 10.

The critical smoke densities were consistently lower for the protans than the colour normal and the deutan groups. The inconsistent heights of the columns at the bottom of the figure illustrate the significant interaction between the factors colour vision and exit sign; the higher columns tend to be associated with red signs, showing that protans were systematically penalized by signs having proportionally more energy in the long wavelengths.

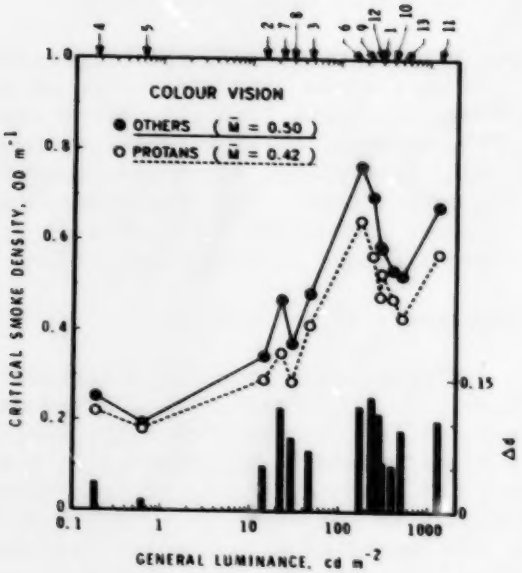

Figure 10. Critical smoke densities for the 13 exit signs for the group of protans and for the group of colour normals and deutans (others) tested in this experiment (sign numbers at top). Mean values of critical smoke density for the two groups of subjects are inset. Columns at bottom show, for each sign, the difference in critical smoke density (Δd) between the two groups of subjects.

The ANOVA also showed a significant interaction between the factors colour vision and ambient illumination ($p < 0.01$). The differences between critical smoke densities for the protan group and the other two groups were smaller with ambient illumination than without. Long wavelengths will be preferentially transmitted through the cosmetic oil smoke employed in this experiment as indicated by the shift in chromaticity values with increasing smoke density (Figure 3). Proportionally more energy at long wavelengths will, therefore, be available to all subjects without ambient illumination than with ambient illumination. This fact and the reduced sensitivity of protans to the proportionally higher energy at long wavelengths when ambient illumination was 'off' likely produced this significant interaction.

No other factor interacted with colour vision to a significant degree in the ANOVA ($p > 0.05$).

It is possible to make some coarse quantitative comparisons between these data and predictions from the literature. From documented spectral power distributions for appropriate lamps and from typical spectral sensitivity functions for different classes of observers, it is possible to predict the luminous efficiency of a given light source for protans or deutans relative to colour normal observers. In making the quantitative comparisons, it was assumed that the spectral power distributions of cool-white fluorescent[16] and incandescent[16] lamps could be used to characterize the light emitted from the exit signs, despite the fact that

they all had coloured, translucent fronts. The two deuteranomalous subjects used in this experiment are not expected to have luminous efficiencies substantially different from colour normals.[19] Because the data from these two subjects were not significantly different from those of the colour normal group, the data from the protan group were compared to all other subjects (colour normals and deutans). It was also assumed that a spectral sensitivity function for protanopes[16] (Figure 9) could characterize the spectral response of the group called protans, which in fact also included protanomolus individuals who are more sensitive than protanopes to long wavelengths (Table II). These two assumptions introduce errors that tend to cancel each other. The relative spectral power distributions of the red exit signs were actually higher in the long wavelength region than characterized by the light sources alone, but, to partially compensate, the spectral sensitivity of the protan group was knowingly underestimated in this region of the spectrum.

The reduction in luminous efficiency for protans relative to colour normals is 13% for a cool-white fluorescent source, and 17% for an incandescent source operating at 2856 K. These estimates agree favourably with the differences in critical smoke densities observed between the protans and the other subjects, indicated by the heights of the columns at the bottom of Figure 10. For those signs with red lettering on dark backgrounds, the overall difference between protans and colour normals in terms of observed critical smoke densities was about 20%.

There are also some finer points that support the hypothesis that colour vision contributed to the differences shown in Figure 10. It was argued in the previous section that subjects used rods to detect Signs 4 and 5 in the absence of ambient illumination. Rod vision is the same for protans, deutans and colour normals. As can be seen in Figure 10, both groups have nearly the same detection threshold for these signs, as expected. Further, the brighter green signs (2 and 10), seen with cones, produced shorter columns than the red signs in Figure 10. This is also expected; to protans, compared to other people, red signs would be relatively less efficient than green signs.

F. The age of subjects

Age, like colour vision, cannot be selectively assigned to subjects. Other physiological and psychological factors affecting vision can be confounded with the age of the observers. Nevertheless, age was included in yet another ANOVA along with the original three experimental variables (exit sign, threshold criterion, and ambient illumination). The 16 observers were arbitrarily divided into six age groups (a) under 21, (b) 21-30, (c) 31-40, (d) 41-50, (e) 51-60, and (f) over 60 years. Age groups were significantly different ($p < 0.001$) in the ANOVA, but none of the other factors interacted significantly with the factor age ($p > 0.05$).

Figure 11 shows the average critical smoke densities for the six age groups. The significant decrease in visibility observed by the middle age groups is not consistent with the literature[20-23] and is likely due to a confounding of age group with colour vision. Two of the three observers in the 31-40 age group were protans with reduced visual efficiency (Table II). Further, all protan observers were confined to the three age groups associated with the lowest critical smoke densities (Figure 11, Table II).

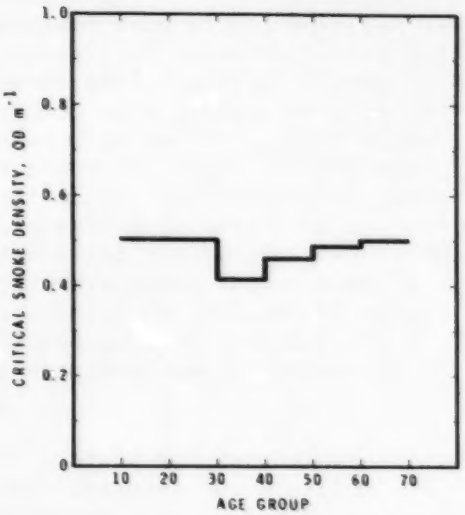

Figure 11. Critical smoke densities for the six age groups of subjects tested in this experiment as a function of general luminance.

A wide body of published data indicates that the human visual system deteriorates steadily, with increasing rate, from about the age of 20. Although there is a good deal of variation within age groups, retinal illuminance is reduced approximately threefold between the ages of 20 and 60. Such detrimental age effects were not evident in this experiment, perhaps because the small sample was not representative of the population at large. Nevertheless, these inevitable and irreversible depreciations in visual capacity with age are worthy of consideration and future experimentation.

IV. CONCLUSIONS AND RECOMMENDATIONS

Several factors were found to be important to exit sign visibility through smoke. Some of these factors were directly associated with the characteristics of signs, and it appears that design recommendations for traditional, 'static' exit signs can be improved. Other factors associated with the building and the observer also influence exit sign visibility. Recognizing all of these factors and developing new strategies for improving exit sign visibility could make buildings safer.

Of course, safety is only one feature to consider in the design and the operation of a building. Energy usage, aesthetics, reliability, and cost are also important constraints on the final building character. They cannot be ignored, and final recommendations and solutions should reflect these constraints as well.

A. Sign Brightness

An object cannot be seen without having some luminous contrast with its background. Dim exit signs quickly lose luminous contrast in smoke; bright

signs will be detectable through much higher smoke densities. Equipping trans-illuminated signs with compact, fluorescent lamps would likely improve the brightness, and thus enhance the visibility, of these signs through smoke. Just as the sign must have luminous contrast with its background, the lettering on a sign must also have luminous contrast with its background (i.e. the sign face) for it to be readable. Signs with, for example, trans-illuminated letters and opaque faces (i.e. cutout or stencilled signs) will have high contrast lettering. Presently, no Canadian national sanctioning body provides adequate specifications for exit sign brightness or letter contrast.

It has been argued that the readability of exit signs in clear conditions can be reduced if they are too bright.[2-3] This argument can be somewhat misleading. Unlike readability, the detectability of the sign may not be reduced if it is brighter. Although a person may not be able to read an exit sign, he or she may still know that a relatively bright and coloured light positioned over a doorway is an exit sign. This knowledge would also aid safe egress. More importantly, however, a dim sign cannot be read nor can it be detected in smoke, and therefore will not provide assistance for safe egress. Brighter signs will be more detectable, even in clear conditions, at distances beyond the person's readability limit.[8,24] Knowing that the bright (but perhaps unreadable) light in the distance is an exit sign will also increase the occupants' chances for safe egress.

Architects and interior designers may, however, find bright exit signs unacceptable for aesthetic reasons. They are concerned primarily with the appearances of the building and its interior; any implanted and highly visible safety feature that detracts from the aesthetics of their design may be difficult for them to accept. An attempt should be made to work with architects and interior designers before legal requirements are made for exit sign brightness.

B. Sign Colour

North America has traditionally, but not exclusively, employed the colour red in exit sign design, often in concert with other, red fire protection equipment. Green, on the other hand, has been used most often in Europe and now is being used increasingly in the United States. Without knowing the spectral power distribution of the light source and the spectral transmission or reflectance of the coloured filter or surface, it is impossible to accurately determine whether red or green signs will be more luminous and, thus, more visible. In principle, however, green trans-illuminated signs should be brighter. Certainly the dominant visible wavelengths transmitted by these signs should be more efficacious to protan (red insensitive) observers. Nevertheless, one has no assurances about the apparent brightness of the sign from a qualitative description of its colour, and useful recommendations must account for the physics of the light, the spectral sensitivity of the individual, as well as the spectral transmission and scatter characteristics of the smoke.

Any coloured sign will transmit less light and therefore will be less bright than a white one with the same broad-band wavelength light source. Based only upon a criterion of photometric luminance, exit signs should not be coloured. However, colour can help people discriminate between an exit sign and another white, luminous source, like a ceiling fixture. It may be

more important, then, to have a coloured sign with somewhat lower luminance than a white sign of higher luminance that might be confused with other light sources in the building. An experiment exploring this hypothesis should be conducted.

The psychological effects of green versus red for exit signs have not been properly studied here or elsewhere. These effects might influence the likelihood that a person will find an exit. For example, a person's expectations about the meaning of green or red may have some impact on his or her chances for safe egress. The importance of these psychological effects, however, should not be over emphasized in making exit sign recommendations until credible data are available.

C. Spatial characteristics of the sign

Although the size of the sign and the letters on the sign were not specifically studied here, larger signs will typically be more detectable,[25] and larger letters on signs will be more readable in smoke and over greater distances.

Unevenly lit lettering will probably be more difficult to read in smoke than uniformly lit letters. Luminous surrounds and downlights will also reduce one's ability to read the exit sign lettering in smoke because of the scatter they produce. Detectability, and perhaps the information content conveyed by the sign, might not be limited, but this is not known for certain. The significance of all these spatial factors in limiting the information conveyed by the exit sign should be studied more carefully in situations similar to those encountered in real buildings.

D. Recommendations for 'static' exit signs

This study has only considered 'static' signs that do not change their luminous characteristics in response to environmental changes. It is possible to make some preliminary recommendations for static signs from the data collected in this study and the arguments presented before in this section:

1) In order to be visible in smoke the sign should be as bright as possible. Under these conditions electric, trans-illuminated signs are clearly better than self-luminous signs and those signs relying on reflection. However, practical and aesthetic constraints can (and should) influence the final luminance recommendations.
2) The sign should be coloured. Although this has not been clearly established, the colour of the sign should help a person discriminate between other luminous sources in smoke. Green seems a logical colour choice due to its (likely) higher luminous efficacy.
3) The sign and its lettering should be large. Large displays are easier to see.
4) Signs should be designed to enhance the luminous contrast of the text and to minimize sources of scattered light outside the area required to read the lettering. Luminous sign faces and down-lights will limit the contrast of the exit sign letters in smoke and thus reduce their readability.

In short (if a conventional, static exit sign must be recommended) a bright, green, large, cutout exit sign will likely be the most visible (detectable and readable) in a smoke-filled environment.

E. 'Smart' signs

Bright signs are not needed under all conditions. In non-emergency situations, people still want to find an exit, and relatively dim exit signs will serve this purpose. Also, in totally dark interiors (e.g. after a power failure) a very bright sign may create direct glare[20-23] and actually limit one's ability to traverse a cluttered space.[26] As mentioned before, very bright signs may also detract from the aesthetic qualities of the building interior. Therefore, signs that are bright in smoke but dim at other times would be advantageous. Photoelectric or ionization detection of smoke could, for example, signal an increase in exit sign brightness. Similarly, a flashing exit sign would be impractical for every day operation, but, if activated after smoke detection, the detectability and the discriminability of the exit sign might be enhanced in a smoke filled interior.

The visibility of exit signs in smoke is reduced by scattered ambient illumination. Therefore, it is advantageous to extinguish or lower the level of ambient illumination near an exit sign in smoke. Fire safety has been a neglected aspect of automatic, centralized lighting control systems. Such systems can be designed to extinguish or dim lights that would otherwise reduce exit sign visibility in smoke. Similarly, an automated lighting control system could extinguish the exit sign downlights, perhaps useful in clear, no-smoke conditions, but deleterious in smoke-filled interiors.

It seems important to develop integrated fire protection strategies based upon sound principles of visibility. More work obviously needs to be done in this area, but this study has already led to useful guidelines that could be incorporated into a fire protection strategy for buildings in Canada and abroad.

Acknowledgements

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Appendix A

Comprehensive description of the exit signs

The approximate area and location of the region of each exit sign face used for measurements of 'general luminance' are illustrated by dashed circles. These measurements were obtained both with and without room lights and are reported as 'GL on' and 'GL off' respectively in units of cd m^{-2}.

Measurements of 'general illuminance' were obtained from the front and from below each sign and are reported as 'GI front' and 'GI below' respectively in units of Lux. Those signs with 'GI below' > 0 were equipped with down light apertures.

Fields labeled '(T)' and '(O)' were trans-illuminated and opaque, respectively. The colour of each field is described qualitatively (e.g., white, red, green, black) and, when transilluminated, in units of CIE (x, y) chromaticity coordinates.

The regions used for spot photopic luminance measurements are illustrated by small solid circles and are reported in units of cd m^{-2}.

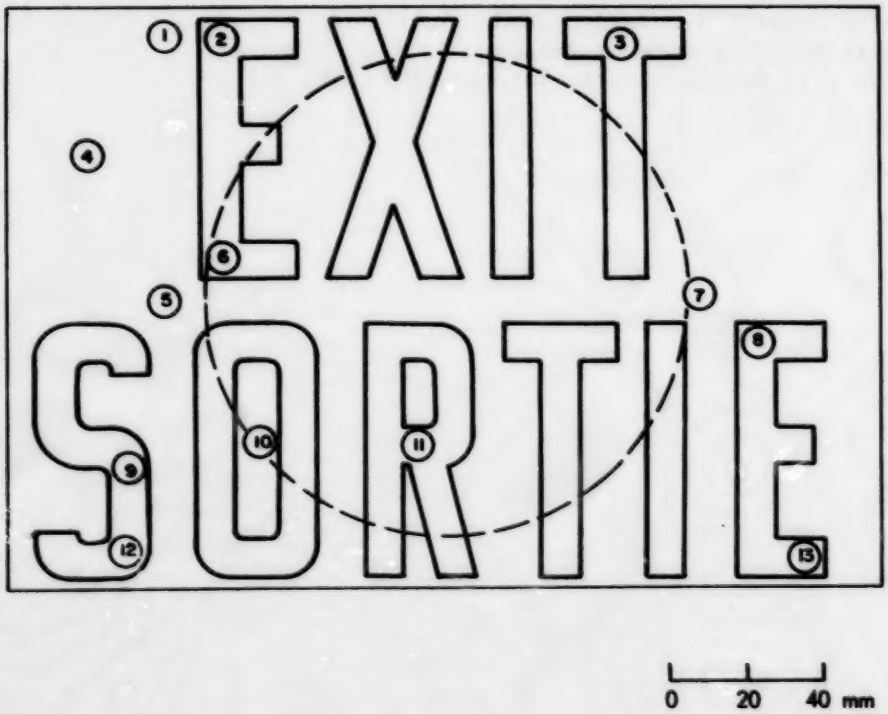
FCC = Fire Commissioner of Canada
CGSB = Canadian General Standards Board
NBC = National Building Code of Canada
GLE = GLE Inc., 14 Connell Court, Toronto, Ont. M8Z 1E7

Sign 1 : Meets the requirements of FCC.
Lettering : French and English. Height = 68 mm
Source : Two 25W frosted incandescent lamps

Field		Colour		
Text	(T)	Red (0.72, 0.28)	GL off	291
Background	(T)	White (0.55, 0.39)	GL on	292
Surround	-	-	GI front	58
			GI below	38

SPOT LUMINANCES

(1)	157	(2)	38	(3)	41	(4)	267	(5)	771	(6)	145	(7)	744
(8)	94	(9)	55	(10)	312	(11)	60	(12)	31	(13)	40		

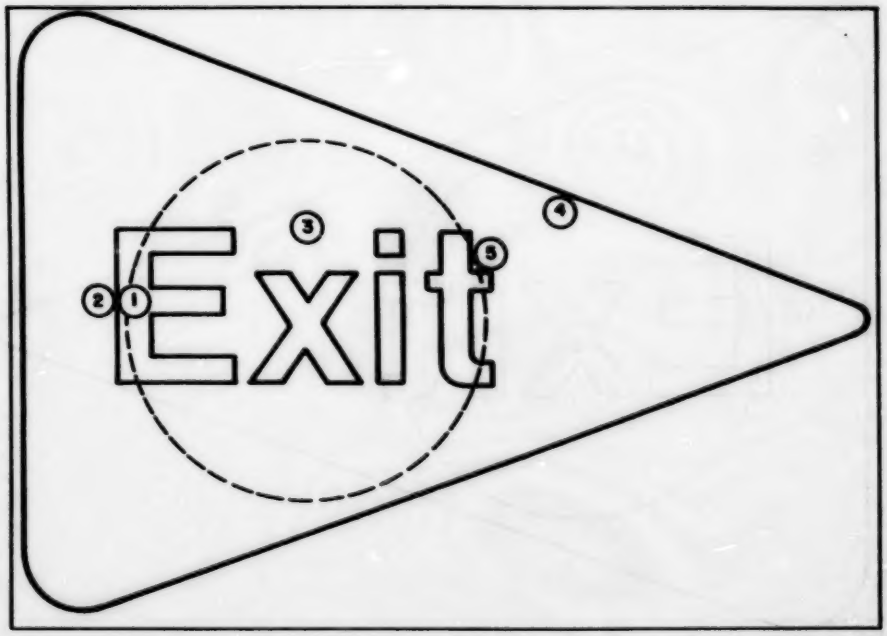


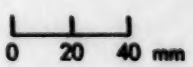
Sign 2 : Meets the requirements of CGSB (see Sign 10)
Lettering : English. Height = 53 mm
Source : Two 15W incandescent lamps

Field		Colour
Text	(O)	Black
Background	(T)	Green (0.36, 0.59)
Surround	(O)	Black

GL off	14
GL on	18
GI front	1.2
GI below	7.4

SPOT LUMINANCES
(1) 0.2 (2) 4.9 (3) 42.0 (4) 41.0 (5) 16.0

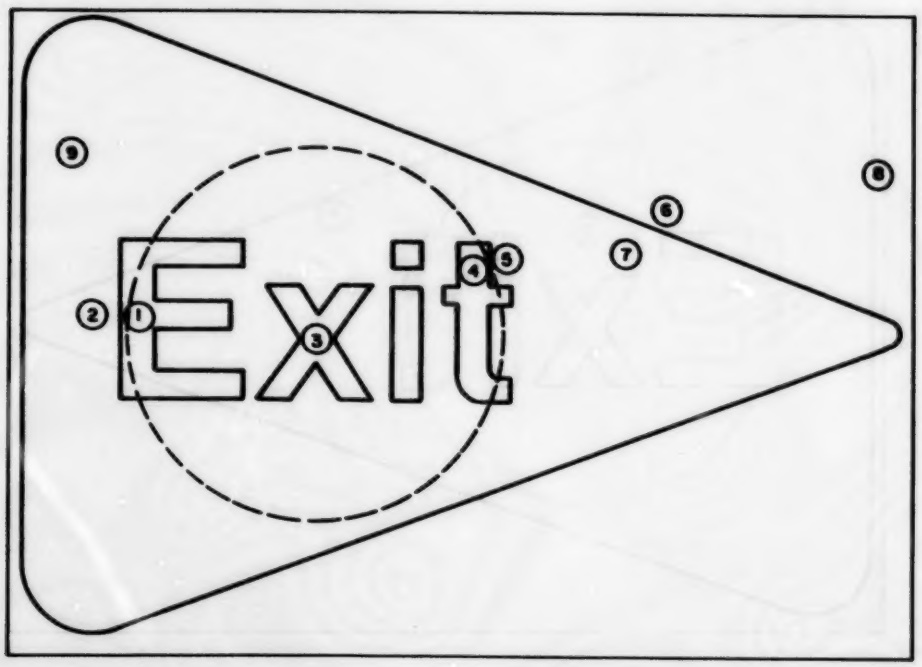


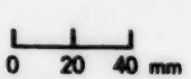


Sign 3 : CGSB prototype (see Sign 11)
Lettering : English. Height = 53 mm
Source : Two 15W incandescent lamps

Field		Colour		
Text	(T)	White	(0.59, 0.37)	GL off 46
Background	(T)	Red	(0.73, 0.27)	GL on 51
Surround	(T)	White	(0.59, 0.37)	GI front 11.6
				GI below 6.3

SPOT LUMINANCES
(1)36.8 (2) 8.1 (3) 71.8 (4)110.0 (5) 25.5 (6)313.0 (7) 59.3
(8) 5.3 (9)11.8



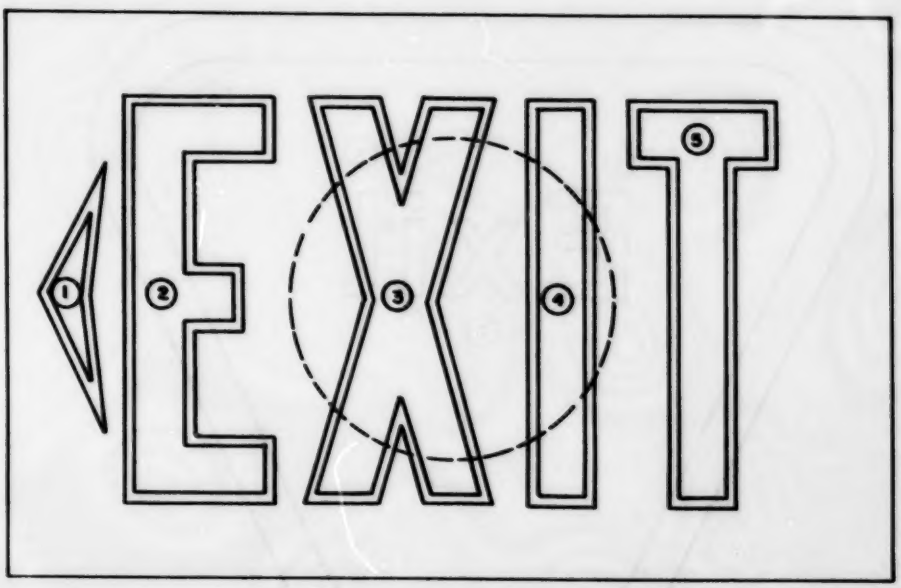


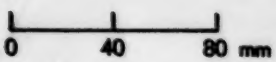
Sign 4 : Supplied by GLE
Lettering : English. Height = 159 mm
Source : Self-illuminated by 25 Cu. tritium-induced chemiluminescence

Field		Colour
Text	(T)	Green (0.29, 0.63)
Background	(0)	Red
Surround	-	-

GL off	0.18
GL on	12
GI front	<0.1
GI below	0

SPOT LUMINANCES
(1) 0.9 (2) 0.8 (3) 0.9 (4) 0.9 (5) 0.6





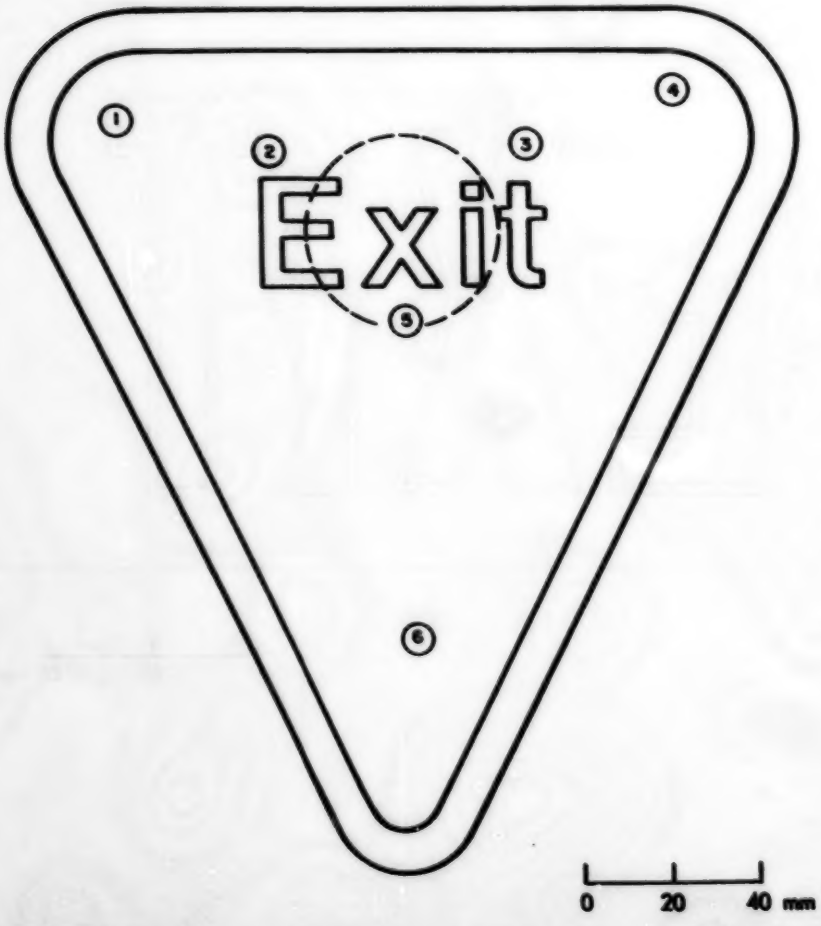
Sign 5 : Supplied by GLE
Lettering : English. Height = 25 mm
Source : Self-illuminated by 25 Cu. titium-induced chemiluminescence

Field		Colour
Text	(O)	Black
Background	(T)	Green (0.29, 0.66)
Surround	-	-

GL off	0.61
GL on	19
GI front	<0.1
GI below	0

SPOT LUMINANCES

(1) 1.3 (2) 1.3 (3) 1.3 (4) 1.3 (5) 1.3 (6) 1.1

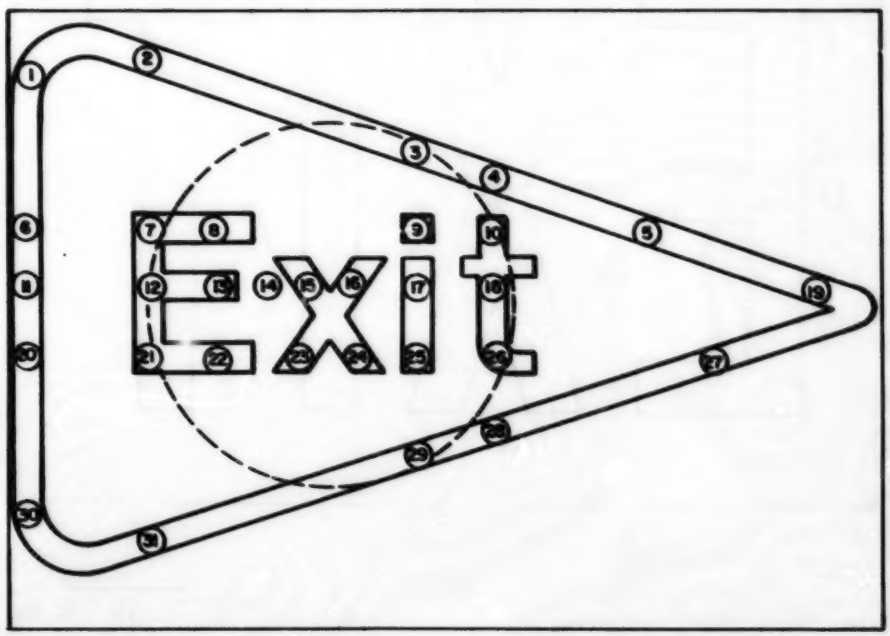


Sign 6 : NRC/DBR prototype
Lettering : English. Height = 54 mm
Source : One 7W and one 9W fluorescent lamp

Field		Colour			
Text	(T)	Red	(0.63, 0.31)	GL off	170
Background	(O)	Black		GL on	170
				GI front	30.2
				GI below	0

SPOT LUMINANCES

(1)	193	(2)	290	(3)	1109	(4)	936	(5)	481	(6)	218	(7)	190
(8)	886	(9)	1035	(10)	926	(11)	217	(12)	97	(13)	201	(14)	5
(15)	324	(16)	330	(17)	292	(18)	302	(19)	214	(20)	175	(21)	74
(22)	206	(23)	249	(24)	262	(25)	218	(26)	195	(27)	63	(28)	290
(29)	293	(30)	89	(31)	63								

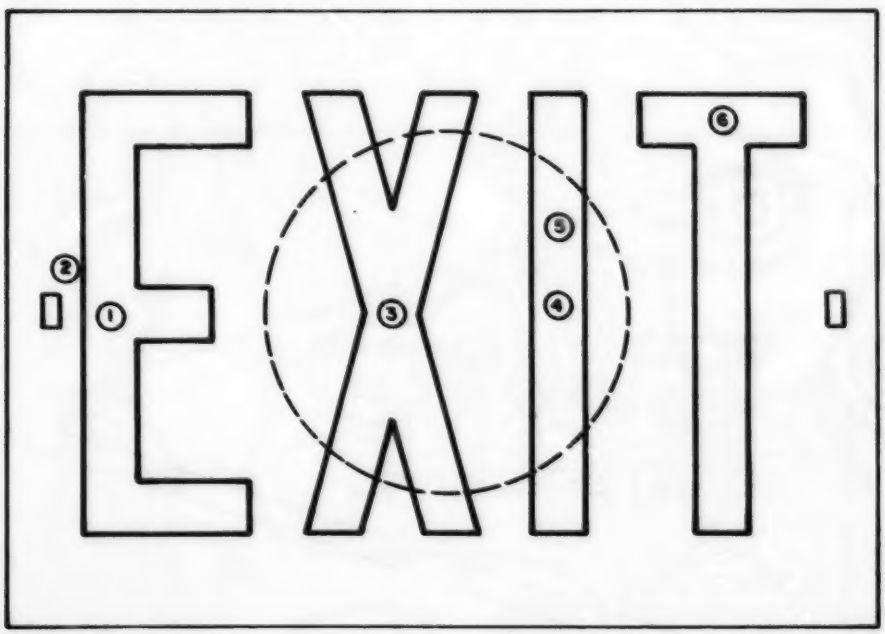


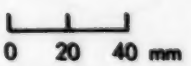
Sign 7 : Meets the requirements of NBC (see Sign 12)
Lettering : English. Height = 152 mm
Source : Two 15W incandescent lamps

Field		Colour		
Text	(T)	Red (0.74, 0.26)	GL off	22
Background	(O)	White	GL on	36
Surround	-	-	GI front	2.3
			GI below	4.1

SPOT LUMINANCES

(1) 11 (2) 0 (3) 32 (4) 37 (5) 92 (6) 14



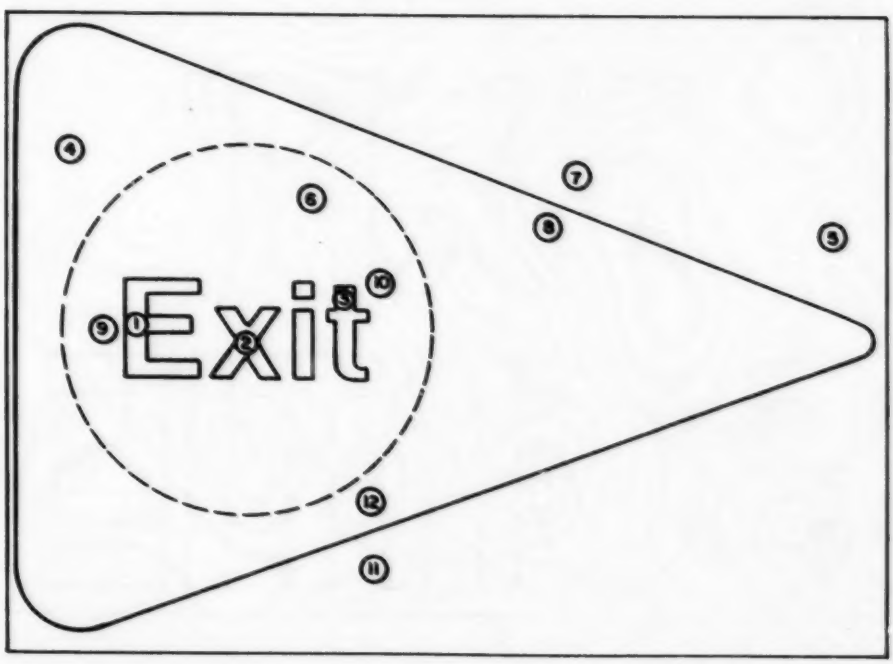


Sign 8 : CGSB prototype (see sign 13)
Lettering : English. Height = 33 mm
Source : Two 15W incandescent lamps

Field		Colour			
Text	(O)	White		GL off	29
Background	(T)	Red	(0.73, 0.26)	GL on	38
Surround	(T)	White	(0.60, 0.36)	GI front	8.1
				GI below	8.0

SPOT LUMINANCES

(1) 5.8 (2) 9.6 (3) 18 (4) 7.5 (5) 14 (6) 59.1 (7) 107
(8) 68 (9) 9.4(10) 34 (11) 4.5 (12) 3.8



Sign 9 : Meets requirements of FCC
Lettering : French and English. Height = 57 mm
Source : Two 25W frosted incandescent lamps

Field		Colour		
Text	(T)	Red (0.73, 0.28)	GL off	232
Background	(O)	Dark Brown	GL on	231
Surround	-	-	GI front	36.5
			GI below	35.7

SPOT LUMINANCES

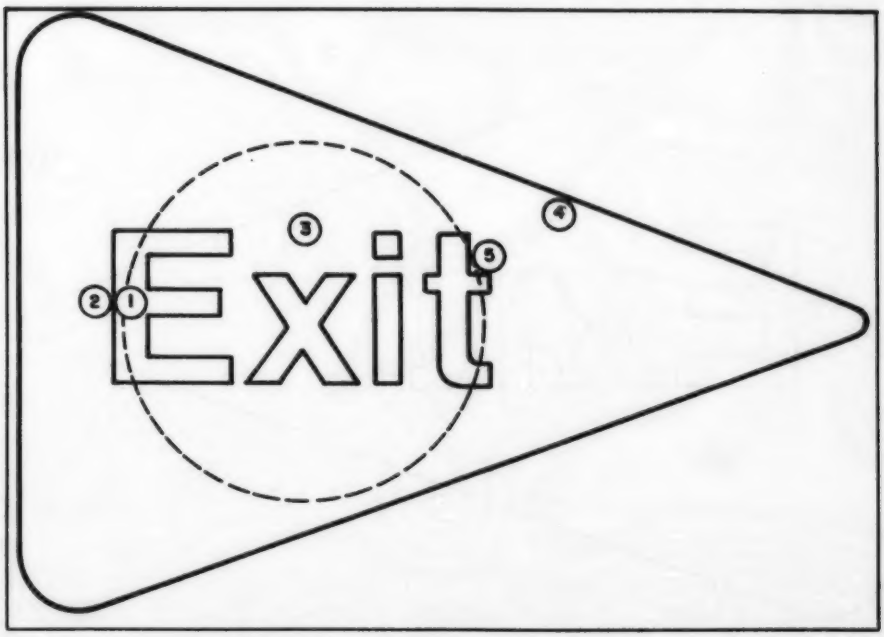
(1) 81 (2) 127 (3) 159 (4) 2184 (5) 134 (6) 128 (7) 114
(8) 64 (9) 103(10) 256 (11) 548(12)2055 (13) 568 (14) 278
(15)474(16) 207

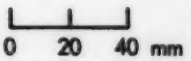
Sign 10 : Sign 2 with fluorescent source
Lettering : English. Height = 53 mm
Source : One 9W fluorescent lamp

Field		Colour
Text	(O)	Black
Background	(T)	Green (0.34, 0.62)
Surround	(O)	Black

GL off	391
GL on	391
GI front	52.1
GI below	123.8

SPOT LUMINANCES
(1) 1.1 (2) 80.1 (3) 308 (4) 313 (5) 630



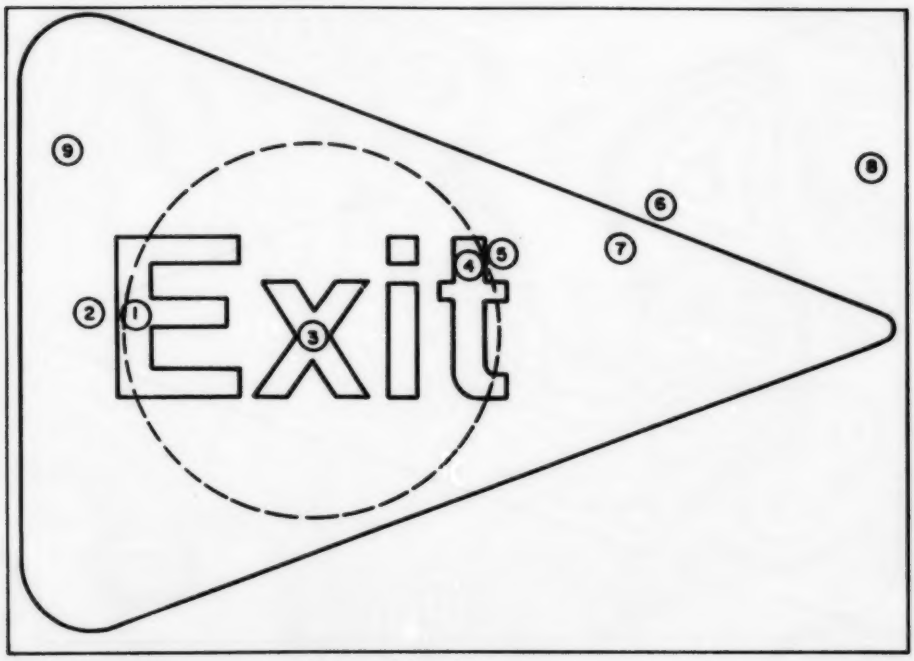


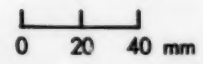
Sign 11 : Sign 3 with fluorescent source
Lettering : English. Height = 53 mm
Source : One 9W fluorescent lamp

Field		Colour		
Text	(T)	White	(0.50, 0.39)	GL off 1277
Background	(T)	Red	(0.70, 0.29)	GL on 1272
Surround	(O)	White	(0.50, 0.39)	GI front 240
				GI below 105

SPOT LUMINANCES

(1) 662 (2) 91.1(3) 4370 (4) 5138 (5) 750 (6) 1134 (7) 210
(8) 66.0(9) 159



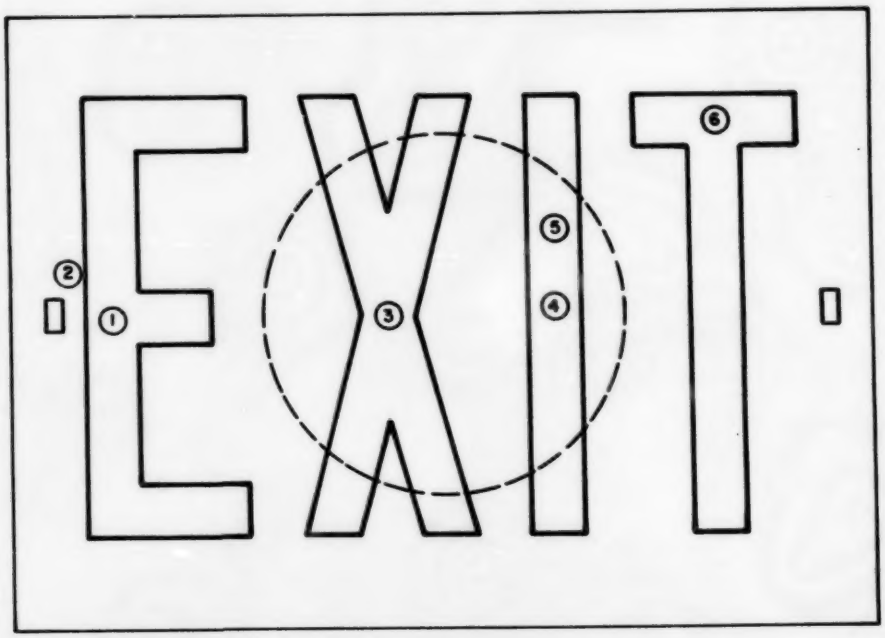


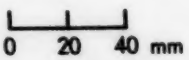
Sign 12 : Sign 7 with fluorescent source
Lettering : English. Height = 152 mm
Source : One 9W fluorescent lamp

Field		Colour	
Text	(T)	Red	(0.71, 0.29)
Background	(0)	White	
Surround	-	-	

GL off	281
GL on	342
GI front	29.5
GI below	65.6

SPOT LUMINANCES
(1) 981 (2) 0 (3) 919 (4) 675 (5) 413 (6) 51



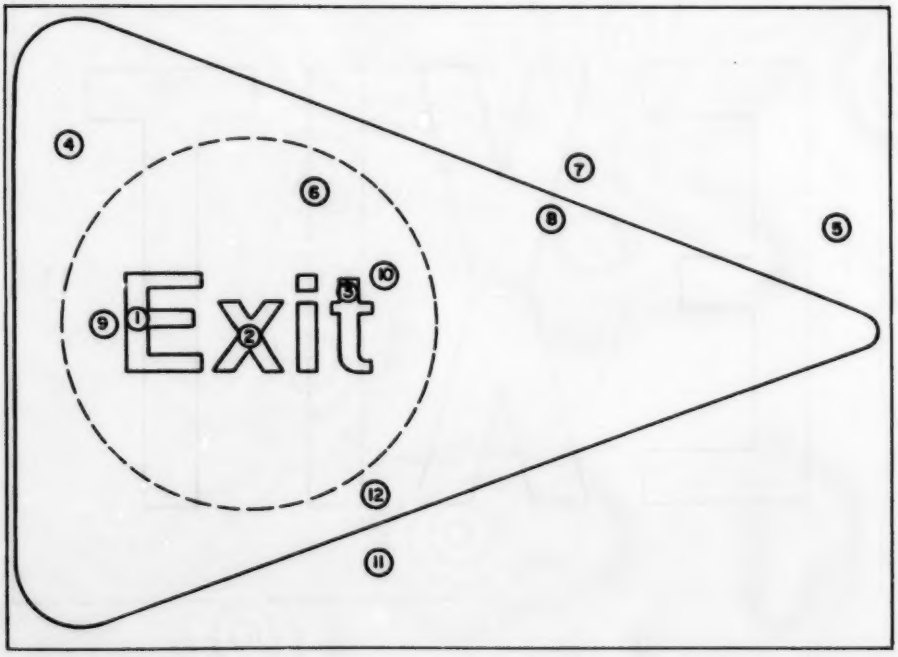


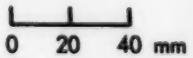
Sign 13 : Sign 8 with fluorescent source
Lettering : English. Height = 33 mm
Source : One 9W fluorescent lamp

Field		Colour		GL off	498
Text	(O)	White		GL on	506
Background	(T)	Red	(0.73, 0.26)	GI front	117
Surround	(T)	White	(0.60, 0.36)	GI below	212

SPOT LUMINANCES

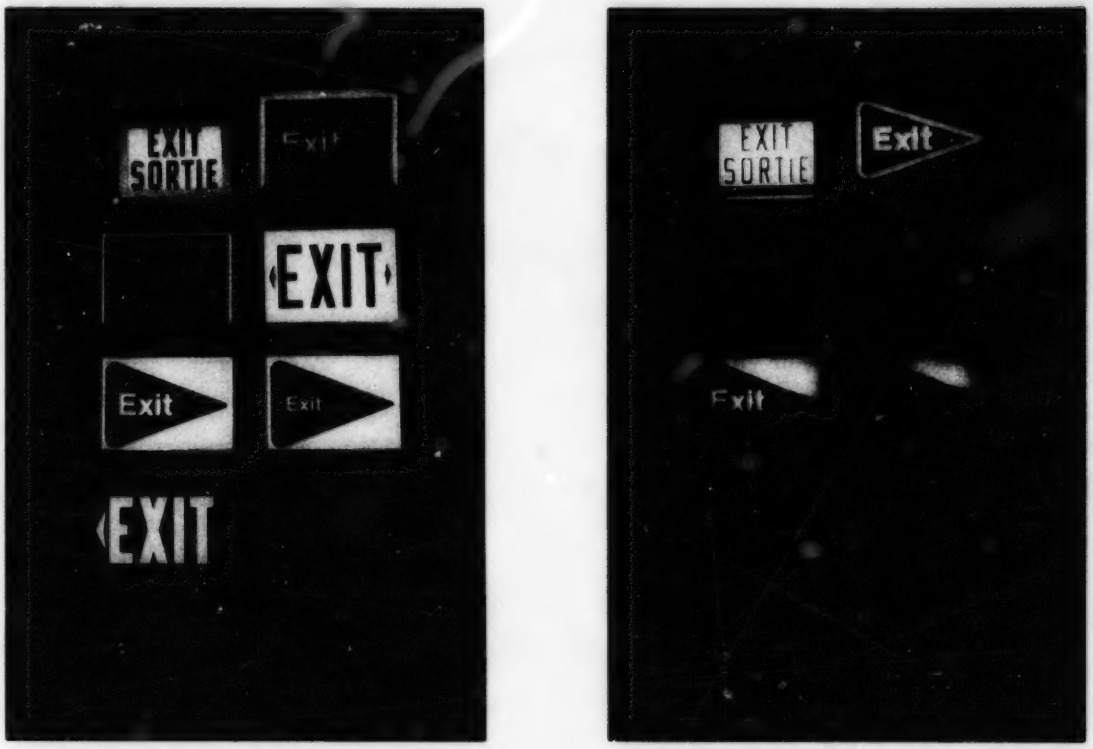
(1) 40.9 (2) 158 (3) 266 (4) 57.6 (5) 82.5 (6) 253
(7) 394 (8) 218 (9) 87 (10) 617 (11) 471 (12) 259





Appendix B

Photographs of the exit sign array as seen by the experimental subject



(a) with room lighting

(b) in the dark

Such photographs can only approximate the appearance of the signs in these two lighting conditions.

Appendix C

Photometric comparisons of ten exit signs, operating when the fluorescent room lights were either 'on' or 'off', were made using three types of smoke. Blocks of black butyl rubber and cellulosic press board were separately burned in a Rohm & Haas XP2 smoke chamber[27], and the smokes produced by these substances were introduced into the smoke chamber in the manner decribed in Section II.A.3. Photometric measurements (Section II.B.2) of the exit signs were made through these two types of smoke and through the cosmetic oil smoke used in the main experiments at matched densities of 0.33 OD m^{-1}, as determined by the helium-neon laser monitoring device (Section II.A.4).

The smoke generation from the Rohm & Haas device was not as well controlled as with the Les Enterprises MDG device, and the wood and rubber smoke entered the viewing chamber while making the photometric measurements. Due to the hazardous nature of these smokes, the two experimenters used self-contained breathing apparatus while making the measurements. With the short air supply contained in these breathing apparatus and the number of measurements required, the photometric measurements of these signs were made relatively quickly through the wood and rubber smoke. The single measurement data are presented in Table C-I. Based upon the similar luminance ratios (O/W and O/R) for all signs, the better controlled, and less hazardous, oil cosmetic smoke was used exclusively in the main experiments. However, inferences about the performance of these exit signs in wood and rubber smokes can likely be made using the median ratios in Table A-I as a correction factor for smoke density.

TABLE C-I

General luminance of signs in a 0.33 m^{-1} smoke density[1]

Sign number	Room lights 'on'					Room lights 'off'				
	O	W	O/W	R	O/R	O	W	O/W	R	O/R
1	64	68	0.94	25	2.6	5.3	7.1	0.75	4.1	1.3
2	70	73	0.96	16	4.4	0.16	0.19	0.84	0.16	1.0
3	52	53	0.98	9.3	5.6	0.58	0.64	0.91	0.46	0.3
7	73	73	1.0	25	2.9	0.37	0.34	1.1	0.32	1.3
8	61	79	0.77	25	2.4	0.14	0.48	0.29	0.39	1.2
9	61	59	1.0	26	2.4	3.8	3.9	0.97	4.7	0.8
10	74	77	0.96	20	3.7	4.4	4.6	0.96	3.5	1.3
11	66	66	1.0	21	3.1	15	15	1.0	12	0.9
12	76	76	1.0	27	2.8	3.3	3.5	0.94	3.0	1.1
13	87	86	1.0	32	2.7	7.4	7.1	1.00	7.9	1.2
median			0.99		2.9			0.95		1.1

[1]Data under columns labeled O, W, and R are photopic luminances in cd m^{-2}. Below 3 cd m^{-2} the spectral sensitivity of the human eye shifts gradually to shorter wavelengths. Thus, values below 3 cd m^{-2} may not actually characterize the relative luminosity of the signs.

O : measured through cosmetic oil smoke
W : measured through wood smoke
R : measured through black rubber smoke